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The purpose of this research is twofold: 1. to demonstrate the effectiveness of GIS and spatial analysis as a tool for investigating groundwater contamination; and 2. to show the need for regular water quality testing of private wells. The research was conducted using secondary data freely available to the public and well construction records obtained from the Guilford County Environmental Health Department. The results of this study show GIS to be useful in the study of groundwater contamination and confirm the need for regular water quality tests of private wells. Because regular testing is currently not required, it is rarely done. Water from wells involved in this study was only tested after construction of the well or as a result of an ancillary event at the request of a government agency. Analysis revealed leaking underground storage tanks as the primary source of known groundwater contamination in Guilford Country. Gasoline, heating oil and diesel fuel were the major contaminates. Although counter intuitive, as the impervious surface area increased, so did the incidents of groundwater contamination.

GIS AS AN INVESTIGATIVE TOOL: GROUNDWATER CONTAMINATION AND PRIVATE WELLS IN GUILFORD COUNTY, NORTH CAROLINA

By

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A Thesis Submitted to
the Faculty of the Graduate School at
The University of North Carolina at Greensboro
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Master of Arts

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2008

Approved by

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Committe Chair

To my brother Bob who set the journey in motion

APPROVAL PAGE

This thesis has been approved by the following committee of the Faculty of The Graduate School at the University of North Carolina at Greensboro

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CHAPTER I

INTRODUCTION

Problem Statement

In 1990, private wells were listed as the primary water supply in over 30 percent of North Carolina housing units (U.S. Census, 1990). The families that make these dwellings their home rely on the wells to provide water for cooking, drinking and bathing. Water quality problems can go undetected for many years. Unlike regulated public water supplies which fall under the domain of the 'Safe Drinking Water Act' and are tested at fixed intervals, private wells have no mandatory testing requirements: The owner of the well or the individual using the water is solely responsible for determining its safety and fitness for use.

It often takes an ancillary event, such as the removal of fuel storage tanks at a service station and the discovery of leaks, to prompt adequate testing. For example, diesel fuel and gasoline from leaking storage tanks can migrate off site both through the soil and in the groundwater. Due to potential liability issues, leaking storage tanks usually trigger a search for and compulsory testing of any private well within 1000 feet of the contaminate source. Without intervention due to a known incidence of contamination in the immediate area, most wells serving individuals go untested and the water is routinely utilized by household members who do not have full knowledge of its quality or suitability for use as a potable water source.

Further, it is important to remember that water quality tests show conditions at a specific point in time. Testing reveals the condition of the water at the time it was tested, not what it will be like at some future date. A database can be designed and used to track areas known to have been contaminated. This information provides a key to understanding the many factors which make an aquifer venerable to contamination and may be used to demonstrate the need for routine testing of all water supplies. Much of the information needed to build such a database can be found in publicly available tables and databases (table 1).

SOURCE OF DATA	INFORMATION
Pollution Incident Reporting Form (PIRF) DEHNR-DWQ GROUNDWATER SECTION	**Notes:** Information is taken from PIRF forms collected by regional offices **Reporting Frequency:** Daily
Toxic Release Inventory (TRI) http://www.epa.gov/tri/	**Notes:** Contains information on toxic chemical releases and other hazardous waste management activities **Reporting Frequency**: Annual
Hazardous Substances Emergency Events Surveillance (HSEES) http://www.atsdr.cdc.gov/HS/HSEES/hsees.html	**Notes:** Contains information on acute releases of hazardous substances that by law require cleanup or neutralization. Also contains information on threatened releases which result in evacuations or other public health action. **Reporting is Voluntary.** Not all states participate
STORET http://www.epa.gov/storet/	**Notes:** Contains water quality data collected from 1999 forward. Raw biological, chemical, and physical data on surface and groundwater.
National Response Center (NRC) http://www.nrc.uscg.mil/nrchp.html	**Notes**: Contains data related to oil and chemical spills.
NCDENR, Division of Waste Management	**Notes**: Provide access to data on inactive hazardous waste sites and underground storage tanks

Table 1. Government data available to the public

An example of such a database is the Pollution Incident Reporting Form (PIRF) database. The release of hazardous chemicals to the environment, whether through a spill resulting from a vehicle accident or the discovery of leaking storage tanks, must be reported to the North Carolina Department of Environment and Natural Resources

(NCDENR). Information concerning these events, or incidents, is stored in the PIRF database. The earliest date in the database is 1982; at that time, only 2 groundwater contamination incidents were logged. By 1990 a total of 1,084 incidents resulting in groundwater contamination were found in the PIRF database. In 2006 the number of incidents causing groundwater contamination had grown to 11,886 (Figure 1). These incidents resulted in the contamination of more than 1, 300 wells.

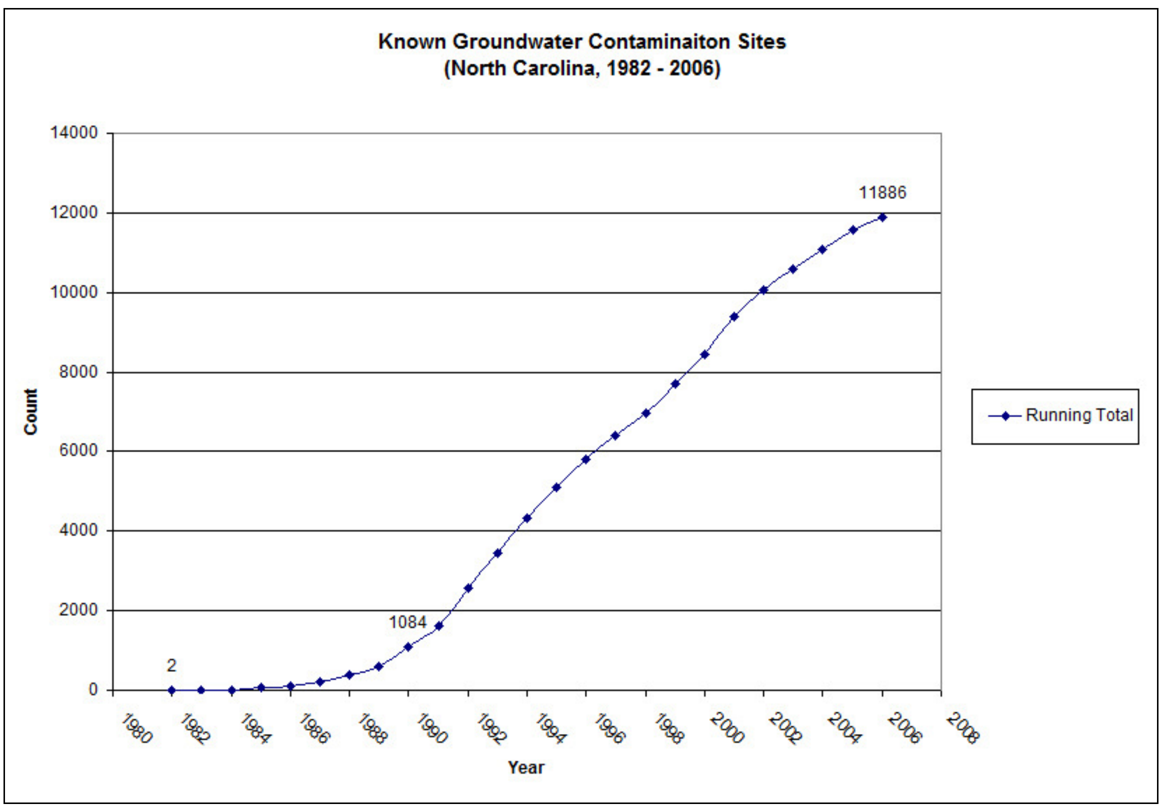


Figure 1. Groundwater Contamination in North Carolina

The PIRF database can be used as a tool to track contamination involving hazardous materials; however, groundwater is also subject to contamination from substances occurring naturally in the environment. Naturally occurring substances which may cause groundwater to become unfit for use as a potable water supply include radon, arsenic, nitrates, fecal coli-form bacteria, and high concentrations of iron and manganese. While this list is not exclusive it demonstrates the array of substances which, when present in drinking water, have the potential to do great harm.

Objectives

The purpose of this research is twofold: 1. to demonstrate the effectiveness of GIS and spatial analysis as a tool for investigating groundwater contamination; and 2. to show the need for regular water quality testing of private wells. The research was conducted using secondary data freely available to the public and well construction records obtained form the Guilford County Environmental Health Department.

Data collected as part of the Guilford County *Well Ordinance Program,* when viewed in conjunction with environmental and administrative spatial data sets, provide a unique opportunity for spatial analysis. Current contamination within Guilford County will be mapped so as to gain an understanding of its distribution and effect on private water supplies. For public health officials and regional planners, an understanding of where, how and why groundwater may become contaminated is vital to the well being of the community both present and future. For that percentage of the population dependent on well water for drinking and bathing, knowledge of where the groundwater is contaminated and where potential contamination sources reside in their community is vital to both their physical and financial well being. It is important that we map areas in which groundwater is currently contaminated and understand the factors which lead to their contamination; by doing so we will be able to identify those elements which create the highest risk to the community and protect those areas most vulnerable.

The analysis performed as part of this study was done entirely with pre-existing data obtained and compiled from various electronic sources, many of which can be freely downloaded from the internet. These include but are not limited to: 1) U. S. Geological Survey (USGS); 2) the North Carolina Division of Water Quality/Groundwater Section Database; 3) North Carolina Division of Public Health State Laboratory; and 4) the North Carolina Division of Waste Management. Information on private wells within Guilford County was obtained from Guilford County Environmental Health Staff.

The advantages of a database management system which would allow environmental health staff to view and edit data, conduct queries and display their results are numerous. Well construction and water quality records which are digitized and linked to a Geographic Information System (GIS) will allow the data to be readily analyzed and spatial trends or patterns to be detected. In areas of known contamination, the drilling of any new wells can be banned. Additionally, city planners would be able to make informed decisions based on the ability of the aquifer to sustain increased development.

The private individual would also benefit from access to a central source of information about potential risks of contaminates; as the well owner assumes primary responsibility for the safety of his/her water, such a database would facilitate private well owner's right to know the current suitability of their vital water source and any inherent future threats to its safety.

CHAPTER II

LITERATURE REVIEW

Ground water is the primary source of drinking water for 55 percent of North Carolinas population. In rural areas this number approaches 97 percent (US Census, 1990). Groundwater in North Carolina is generally of good quality. However, increasing contamination incidents have generated an awareness of its vulnerability to contamination (McLaughlin, et al., 1994). Between January 1982 and December 1992 the North Carolina Department of Environment and Natural Resources (NCDENR) received 2, 578 confirmed reports of groundwater contamination (figure 2). The number of confirmed groundwater contamination incidents grew to 11,892 by July 2006 (Pollution Incident Reporting Form database, NCDENR; figure 3). In the period between 1982 and 1992, ninety-four of North Carolina's one hundred counties reported at least one groundwater contamination incident (Smutko et al., 1993). By 2006 no county had been spared (PIRF, 2008; Figure 4).

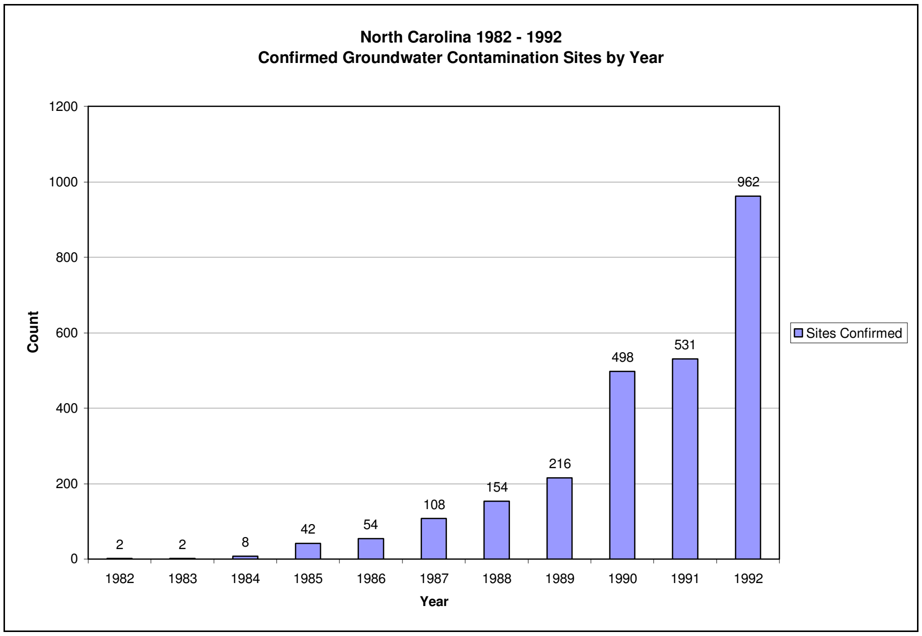


Figure 2. Groundwater contamination 1982 - 1992

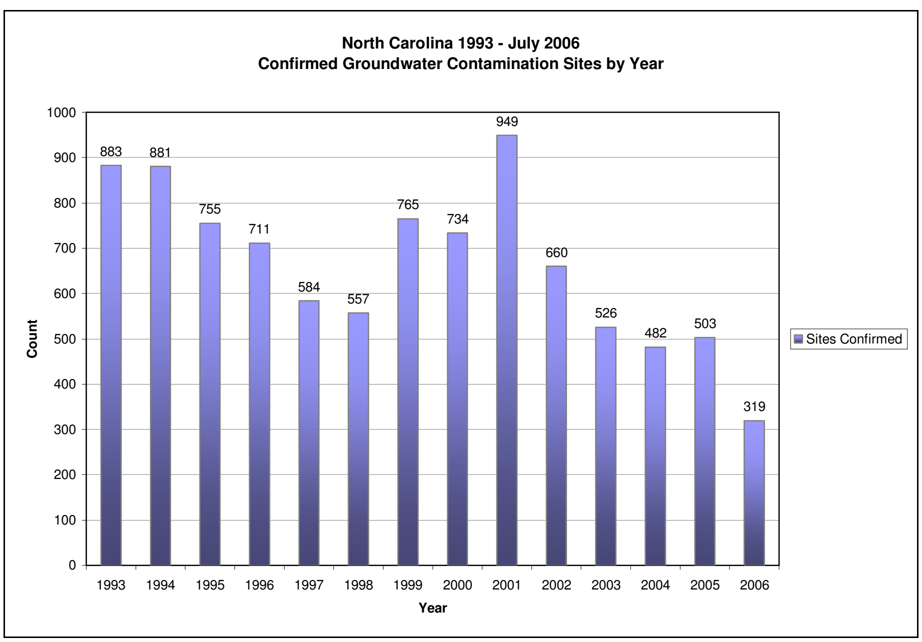
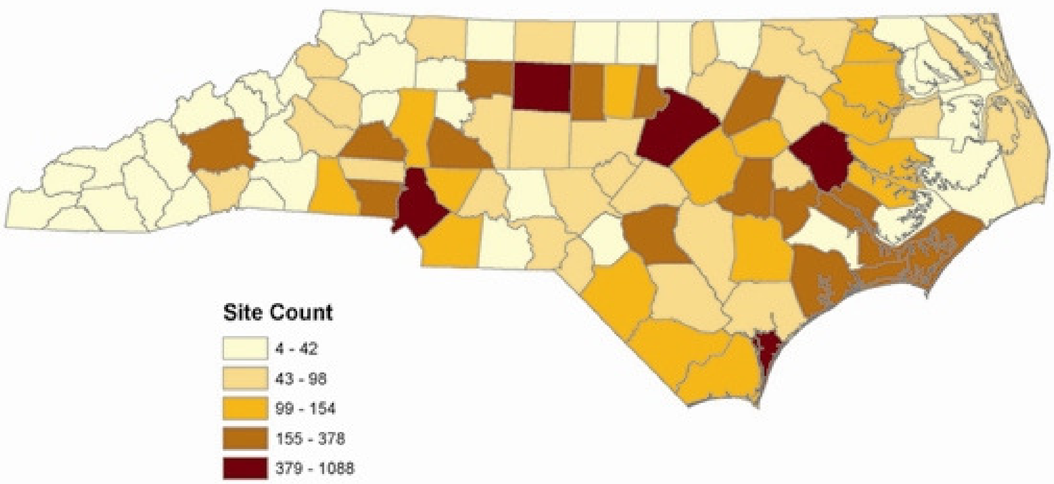


Figure 3. Groundwater contamination 1993 - 2006

Groundwater Contaimination Sites
(by county)



Source: NC Department of Environment Health and Natural Resources
Division of Water Quality, Groundwater Section
PIRF Incident Management Database, January 2008

County	Sites	County	Sites	County	Sites	County	Sites	County	Sites
ALAMANCE	167	CHOWAN	37	GUILFORD	662	MITCHELL	14	RUTHERFORD	35
ALEXANDER	20	CLAY	4	HALIFAX	75	MONTGOMERY	42	SAMPSON	82
ALLEGHANY	8	CLEVELAND	121	HARNETT	92	MOORE	79	SCOTLAND	68
ANSON	15	COLUMBUS	135	HAYWOOD	40	NASH	161	STANLY	92
ASHE	32	CRAVEN	249	HENDERSON	69	NEW HANOVER	453	STOKES	26
AVERY	23	CUMBERLAND	343	HERTFORD	110	NORTHAMPTON	53	SURRY	74
BEAUFORT	154	CURRITUCK	50	HOKE	24	ONSLOW	378	SWAIN	7
BERTIE	118	DARE	98	HYDE	16	ORANGE	99	TRANSYLVANIA	30
BLADEN	50	DAVIDSON	98	IREDELL	140	PAMLICO	30	TYRRELL	10
BRUNSWICK	129	DAVIE	22	JACKSON	33	PASQUOTANK	89	UNION	126
BUNCOMBE	206	DUPLIN	106	JOHNSTON	149	PENDER	89	VANCE	69
BURKE	85	DURHAM	353	JONES	22	PERQUIMANS	29	WAKE	598
CABARRUS	119	EDGECOMBE	93	LEE	71	PERSON	40	WARREN	17
CALDWELL	70	FORSYTH	293	LENOIR	220	PITT	778	WASHINGTON	57
CAMDEN	28	FRANKLIN	44	LINCOLN	61	POLK	12	WATAUGA	50
CARTERET	164	GASTON	245	MACON	18	RANDOLPH	98	WAYNE	247
CASWELL	25	GATES	17	MADISON	12	RICHMOND	77	WILKES	39
CATAWBA	179	GRAHAM	5	MARTIN	127	ROBESON	142	WILSON	117
CHATHAM	76	GRANVILLE	39	MCDOWELL	39	ROCKINGHAM	91	YADKIN	26
CHEROKEE	18	GREENE	53	MECKLENBURG	1088	ROWAN	199	YANCEY	10

Figure 4. Groundwater contamination sites by county 1982 - 2006

Groundwater is vulnerable to contamination from numerous anthropogenic activities. Improperly installed septic tanks, land disposal of wastes, leaking underground storage tanks, and accidental spills are all sources of groundwater contamination in North Carolina (Smutko, S., et al., 1993). Pollution, or the source of contamination, is often described as being point source or nonpoint source. Examples of point sources are spills at industrial sites, leaking underground storage containers, leaking sewer lines and waste lagoons and landfills. Nonpoint sources are more dispersed in nature and include fertilizers and pesticides applied to agricultural fields, contaminants washed from parking lots and roads, in addition too acid precipitation and the dry deposition of airborne pollutants (Fitts, 2002). The terms point and nonpoint do not reflect where the contamination takes place but rather refer to how the contamination is dispersed. Point sources are dispersed locally whereas nonpoint sources are dispersed over wide areas or regions. A leaking pesticide container behind a barn is a point source pollutant while the same pesticide when applied to crops, moving through the regolith assisted by rain or irrigation water, will be classified as a nonpoint source. While the distribution of a pollutant may be classified as point or nonpoint, changes in ground-water quality are closely related to patterns in land-use and waste disposal practices (Giese et al., 1987).

In urbanized settings leaks in sewer lines are a source for direct infiltration of both domestic and industrial effluents. Sewage is known to contain heavy metals, solvents, pharmaceutical compounds, and petroleum products in varying amounts. Human waste is also a source of nitrogen, viruses and various forms of fecal bacteria. The degree to which land use classifications such as industrial, urban or agricultural impact groundwater quality is highly dependent upon its presence and/or expansion within a community. In contrast, pollution from sewage is a potential problem in all inhabited landscapes (Lerner and Barrett, 2004). Lerner and Barrett have linked the expansion of urban areas, and resulting changes in land use, to the lowering of water tables; in addition, they attribute the land disposal of residential and industrial waste to contamination of the shallow aquifers (Lerner and Barrett, 2004).

In trying to assess the impact of human activities on groundwater contamination Moody (1996) grouped potential sources of contamination into four categories: 1) waste disposal, 2) storage and handling, 3) agricultural, and 4) salt water intrusion. Methods of waste disposal commonly associated with groundwater contamination included landfills, septic systems, surface impoundments or lagoons, injection wells, and direct land application of waste. Contamination due to 'storage and handling' included items such as leaking storage tanks, accidental spills, and poor implementation of standards in the handling and transfer of materials. Agricultural sources of contamination included misused commercial fertilizers and pesticides, animal waste found in feedlots and irrigation. Contamination due to saline intrusion was most commonly associated with the over pumping of coastal aquifers (Moody, 1996).

A study conducted by the USGS (Squilance and Moran, 2006) looked for common factors in aquifer systems and groundwater contaminated with volatile organic compounds (VOC). They focused on three factors: 1. Source (where the chemical originated); 2. Transport (how it moved from its source to the aquifer and within the aquifer); and 3. Fate (factors which assisted in its degradation). Important source factors included MTBE (an oxygen enhancer added to gasoline) use areas, Resource Conservation and Recovery Act (RCRA) sites, the presence of underground storage tanks (UST), leaking underground storage tanks (LUST), septic and sewer systems. General land-use characteristics such as the amount of urban land were deemed significant as urban areas or population centers had larger concentrations of these various source factors. Factors found to have a significant impact on the transport of contaminates included the depth of wells, depth of screen placement, precipitation, groundwater recharge, air temperature, and various soil characteristics (Squilance & Moran, 2006; Zogorski, et al., 2006).

Source Factors	
• Septic systems • Urban Land • Resource Conservation and Recovery Act (RCRA) hazardous waste facilities • Gasoline underground storage tank and leaking underground storage tank sites	
Transport Factors	
• Climatic Conditions • Depth to top of well screen • Hydric (anoxic) soils	
Fate Factor	
• Oxic ground water (dissolved-oxygen concentration greater than or equal to 0.5 milligram per liter)	

Table 2. Factors most commonly associated with VOCs in aquifers (Zogorski, et al, 2006).

The relative importance of each of these factors varied by individual VOC, but RCRA, LUST, and UST sites were typically not as important as factors that describe general land-use characteristics. Deeper wells had a smaller chance of VOC detection. In general, areas with high precipitation and groundwater recharge rates contained greater

VOC detections. Cold temperatures were associated with an increased detection of certain VOCs because volatility and biodegradation is reduced with cold temperatures increasing the possibility of VOCs entering the groundwater. Only one factor—dissolved-oxygen concentration—was associated with the fate of VOCs in aquifers (Squilance & Moran, 2006; Zogorski, et al., 2006).

When assessing factors associated with the occurrence of solvents (chloromethane, methylene chloride, TCA, TCE, and PCE) similar results were obtained. Septic system density, percentage of urban land use, and number of RCRA hazardous waste facilities were all identified as sources associated with the occurrence of solvents. Soils high in silt, low in sand, and low in organic matter (factors indicating low permeability) were associated with the occurrence of solvents such as chloromethane and methylene chloride (Moran, Zogorski, & Rowe, 2006). The number of underground storage tank sites was an important source factor associated with the gasoline hydrocarbons (1,2,4-trimethylbenzene and toluene) and also with the gasoline oxygenate MTBE. Leaking undergrounds storage tanks and surface runoff are thought to be the source of these three VOCs. Cool climates which tend to reduce volatilization of VOCs from land surfaces to the atmosphere, showed a significant correlation to the occurrence of 1,2,4-trimethylbenzene, toluene, and MTBE in groundwater. Toluene and MTBE were weakly associated with oxic conditions (Moran, et al., 2006). These studies were important in determining which factors were correlated to the finding of a specific chemical or VOC group in the aquifer. Using statistical methods the vulnerability of a site could be linked to the properties of a specific chemical or chemical group.

Statistical methods for determining vulnerability were also employed by Fuest et al. (1998) when they examined monitoring well records across a region and overlaid these results with spatial information in a GIS system. Troiano, Nordmark, Barry, and Johnson (1997) used a similar approach based on the observation of pesticides in wells across California. Their work characterized the catchment of each well, where pesticides were detected and used a series of multivariate techniques to profile regions that would be vulnerable to groundwater pollution. Their technique identified five clusters of soil and/or climatic variables that represented vulnerable regions. These clusters were later used to assess the vulnerability of regions outside of those in the original study and formed the foundation of a modeling approach to determining a sites vulnerability to pesticide contamination. The California Vulnerability (CalVul) computer model, attempts to identify similar geographic features amongst areas where pesticide residues were previously found in groundwater. This approach is unique in that no apriori determination is made regarding the pathway for pesticide movement to groundwater and no relative scale of vulnerability is derived between land areas (Troiano, Nordmark, Barry & Johnson, 1997).

Another approach to determining vulnerability is though the use of an index and overlay methodology such as DRASTIC (Zhang, Hamerlinck, Gloss, & Munn, 1996; NAS 1993). The DRASTIC method assigns an index value to various layers based upon factors believed to influence vulnerability. Thematic map overlays are generated for depth to groundwater, recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity. Based on their combined index values sites are ranked in degree of vulnerability form high to low (Thirumalaivasan, 2001).

In 1999 the USGS in conjunction with the North Carolina Department of Environment and Natural Resources (NCDENR) developed 11 data sets to rate the susceptibility of public water supplies in North Carolina to contamination. One of these data sets is entitled “Land-Cover Classes to Characterize the Unsaturated Zone”. This data set assigns a rating to various land-cover classes based on the effect they have on infiltration. The rating scale runs form 1 to 10. When assessing groundwater systems there is a presumption that the higher the infiltration rate the greater the likelihood of contamination entering the system. As such areas with forest cover may receive a rating of 10 (high inherent vulnerability) as opposed to highly paved areas which impede infiltration (low inherent vulnerability). The types of land cover present within a region give rise to differing degrees of vulnerability and afford differing degrees of protection to the underlying aquifer. Cunningham and Daniel (2001) used three contributing factors to obtain a relative vulnerability index: soil permeability, land use/land cover, and land surface slope. The index and overlay methodology, assumes vulnerability is as much controlled by the characteristics of a locality as it is dependent upon the nature of the pollutant. The assumption is that with an understanding of the properties which control vulnerability it will be feasible to locate and map vulnerable areas (Worrall & Kolpin, 2004).

Determination of land use/land cover classification patterns, when assessing non point sources of contamination at the watershed scale, can be enhanced by combining

Landsat TM and SPOT panchromatic images (Basnyat, Teeter, Lockaby, & Flynn, 2000). The composite image will have the spatial resolution of the SPOT panchromatic (10 meter) and the spectral resolution of the Landsat TM. In addition, classified land cover data can be obtained from the Multi-Resolution Land Characteristics (MRLC) consortium. The main objective of the MRLC is to generate a generalized and consistent land cover data set for the entire conterminous United States. A study on groundwater quality and availability in Orange County North Carolina was partially based on data obtained from the MRLC (Cunningham & Daniel III, 2001).

While the vulnerability of a site to contamination can be assessed through a variety of means the presence of wells provides a direct channel by which contaminates can enter the aquifer. Personnel with the Guilford County Environmental Health department have reported water in wells being contaminated as a result of surface water entering the well. Surface water infiltration has been linked to improperly constructed or damaged wells. It is common in older wells where liners do not extend into bed rock and existing seals and/or grout have deteriorated. In Guilford County improperly constructed and/or maintained wells have been linked to bacterial and nitrate contamination. It should be noted that naturally occurring water is not pure but rather contains dissolved inorganic and organic materials. Many of these substances are beneficial; others may give the water an objectionable odor or disagreeable taste and some, when ingested over a period of time, may have adverse health effects (Personal Communication, Carl Parsons 2006).

These state-wide and regional studies document a widespread occurrence of contamination in aquifers and have been reported in peer review literature. However, there are a large number of groundwater quality samples and analyses conducted by consulting firms as part of NCDENR watershed studies or in support of assessments of point source contamination. In addition, the North Carolina State Lab maintains a database of water quality tests submitted by county health departments. The information from these studies is not published in peer reviewed literature. Considering the number of studies and the number of groundwater samples collected for these studies, they have the potential to be a valuable source of information on groundwater quality. Further, it seems reasonable to expect that data resulting from studies of point sources of contamination would show that contaminants occur at higher frequencies and at greater concentrations than data from regional studies of groundwater quality conditions.

Wellhead Protection Programs

The 1986 amendments to the safe drinking water act required states to develop wellhead protection programs as part of a national strategy to prevent contamination of groundwater based public drinking water supplies. EPA studies found the cost of remediation to be up to two hundred times the cost of prevention. Not only was prevention more cost effective but it provided a cleaner source of water and thus a less costly means of compliance with the Safe Drinking Water Act (EPA, 1992).

Wellhead protection programs are designed to reduce the threat to the quality of groundwater by managing sources of contamination within the wells recharge area. The wellhead protection area is defined as that area through which contaminants are likely to move and reach a public water system. In order to protect the ‘wellhead’ contamination sources within the wellhead protection area are regulated (EPA, May 1992).

In North Carolina, the state has assumed responsibility for developing standards for wellhead protection programs but has made participation by local governments, i.e. city and county, voluntary. The program has two basic components: 1) identify the wells recharge area; and 2) reduce the number of contaminants entering the recharge area (NCDENR, Public Water Supply Section). Wellhead protection programs are designed to protect public water supplies. Guilford County has not formally adopted the EPA’s wellhead protection program. However the Well Ordinance Program implemented by the Guilford County Department of Environmental Health contains many features designed to protect the aquifer and the public dependent upon groundwater as a primary water supply.

Potential Contamination Source	Distance
Building foundations, excluding the foundation of a structure housing the well head	25 ft
Above ground or underground storage tanks which contain petroleum fuels used for heating equipment, boilers or furnaces	50 ft
Surface water bodies which act as sources of groundwater recharge, such as ponds, lakes and reservoirs	50 ft
Septic tank and drain-field	100 ft
Industrial or municipal sludge-spreading or wastewater-irrigation sites	100 ft
Animal feedlots or manure piles	100 ft
Sanitary landfills	500 ft

Table 3. Minimum allowable distance between well and sources of contamination (15A NCAC 02C .0107)

The program, which went into effect in July of 1989, requires well contractors to register with the county on an annual basis. In addition, permits are required for new well construction and for repairs to existing wells. Employees of the Guilford County Department of Environmental Health enforce state rules on the location of water supply wells (Table 3) and enforce mandatory construction standards such as the type and depth of casing material. All wells are inspected upon completion and tested for coliform bacteria. Additional tests are available and performed at the request of the well owner/user. (http://h2o.enr.state.nc.us/wc/CountyWellRegulationPrograms.htm).

CHAPTER III

DATA AND METHODS

Underground Storage Tanks

An Access database containing information on registered underground storage tanks was obtained from the North Carolina Department of Environment and Natural Resources (NCDENR), Division of Waste Management (http://ust.ehnr.state.nc.us/main.html). Tank locations were added to the map by creating a join between the facility address and the address associated with a parcel. It should be noted that multiple tanks exist at each site. This explains the presence of 5,438 underground storage tanks (UST) on the grounds of 1,188 unique facilities. Records of underground tanks installed before 1993 were extracted by querying the database.

An EPA estimate places leaks from underground storage tanks as the source of 45 percent of all groundwater contamination. Current legislation requires tanks installed after 1993 to have a leak detection system in place. Tanks installed after 1998 must have overfill and spill prevention devices in place; in addition, they must be double walled or housed within concrete vaults (Weiner, 2000).

Well Construction Database

Guilford County began saving well construction records in electronic or digital format in 1991. These records were obtained, from the Guilford County Environmental

Health Department, as a flat file stored within an Access database. An examination of the table showed that 30,050 well application permits had been recorded. Only 18,800 application permits contained records related to well construction. The file did not contain map coordinates for the wells; therefore, well locations were mapped using a process known as geocoding. Geocoding is a method by which map coordinates are assigned to spatial features using a technique such as address matching. This technique would allow each well to be mapped based upon its street address.

The well construction records were queried to find duplicates based upon their street address. As each well could only occupy one point, criteria to determine which record to keep was created. Any records which did not have values related to yield, total depth, and static water level were removed from consideration. For those duplicates still remaining additional criteria were established. These included deleting the well with the smallest yield and/or selecting the oldest well for deletion. While arbitrary, this determination was based on the logic that new wells were installed to replace low yielding wells. The final list contained 7,033 records, each with a unique location and associated well construction records. These records were saved as a dbase table, added to the GIS environment and geocoded. Six thousand eight hundred ninety five records were successfully geocoded and mapped.

Pollution Incident Reporting Form

The Pollution Incident Reporting Form (PIRF) database is maintained by NCDENR, Division of Water Quality, Groundwater Section and was downloaded as an

Access database. The database was queried to limit information to Guilford County. Two thousand one hundred two pollution incidents were reported in Guilford County between 1985 and June 2006. Latitude and longitude coordinates were available for 686 records. Rather than having a mixture of points some based on latitude and longitude, and others based upon the address location a decision was made to geocode all reported locations.

Inorganic Lab Tests

Inorganic lab test results for Guilford County were downloaded from the North Carolina State Laboratory web site (http://slph.state.nc.us) and imported into an Access database. A query was used to extract information based upon the substance being tested. A table was generated for each substance.

Geology

Three digital maps: geol250 (geologic formations); geol250d (dikes); and geol250f (faults) were obtained from NC OneMap. These digital map layers were published by NC DEHNR-Division of Land Resources, NC Geological Survey in 1998. One of the attributes within the coverage is 'GEO_NAME'. This attribute defines the geologic units' age and name. For example CZg is used to indicate Cambrian/Late Proterozoic, Metamorphosed Granitic Rock (table 4).

GEO_NAME	UNIT_AGE	UNIT_NAME
CZg	Cambrian/Late Proterozoic	Metamorphosed Granitic Rock
CZiv	Cambrian/Late Proterozoic	Intermediate Metavolcanic Rock
CZfv	Cambrian/Late Proterozoic	Felsic Metavolcanic Rock
CZfv1	Cambrian/Late Proterozoic	Uwharrie Formation; Felsic Metavolcanic Rock
CZbg	Cambrian/Late Proterozoic	Biotite Gneiss and Schist
CZmv	Cambrian/Late Proterozoic	Mafic Metavolcanic Rock
CZv	Cambrian/Late Proterozoic	Metavolcanic Rock
PPg	Permian/Pennsylvanian	Granitic Rock
PzZg	Paleozoic/Late Proterozoic	Metamorphosed Gabbro and Diorite
PzZu	Paleozoic/Late Proterozoic	Meta-ultramafic Rock

Table 4. Geologic units common to Guilford County (NCDENR, et al., 1998)

Land Use / Land Cover

The Region 14 dataset, which encompasses NC, was downloaded from the Multi Resolution Land Cover Consortium (http://www.mrlc.gov/mrlc2k_nlcd.asp). The data has a resolution of 30 meters per pixel or approximately ¼ acre per pixel. The land cover file is based upon the 2001 National Land Cover Database. It contains four classes of development: 1). Developed, Open Space (impervious surface area is less then 20 percent); 2). Developed, Low Intensity (impervious surface area = 20 to 49 percent); 3). Developed, Medium Intensity (impervious surface area = 50 to 79 percent); and 4). Developed, High Intensity (impervious surface area = 80 to 100 percent).

US Census Bureau

The 1990 census was the last to include questions regarding a household's primary water source. Information was obtained at the block-group level. Attributes included the number of households using: a public system, an individual drilled well, an individual dug well, or some other source. To facilitate mapping and aggregating information the following columns were added to the attribute table: 1. All sources; 2. All individual wells; and 3. Wells as percent of total.

Defining the wellhead protection area

Guilford County is located in the piedmont region of North Carolina and groundwater is found in unconfined aquifers (NCDENR, 2006). An acceptable method for delineation of wellhead protection areas in unconfined aquifers is the calculated fixed radius method. The fixed radius method places the well in the center of a circle and delineates its radius based upon the maximum twelve hour withdrawal and the recharge rate of the aquifer (NCDENR, Public Water Supply Section).

The radius of the wellhead protection area in feet is determined by the following equation:

$$R = 4213 \sqrt{A} \qquad (1)$$

$$A = Q/W \qquad (2)$$

Where:

R = Radius of wellhead protection area
4213 = Conversion factor used to convert area in square miles to radius in feet while doubling the contributing area to account for directional differences in the aquifer.
A = Contributing Area in square miles
Q = Maximum permitted daily withdrawal in gallons per day
W = Average recharge rate in gallons per day per square mile

Public wells have an assumed period of operation equal to 12 hours thus the maximum daily withdrawal for the well (Q) can be determined by multiplying the maximum pumping rate (gallons per minute) by the minutes in a twelve hour day (720). While this methodology was designed for public wells the same technique is used for private wells in this study. All wells used in this study included data on their yield in gallons per minute.

The recharge rate used in this study is an estimated value provided by the NCDENR. Those sections of the county underlain by the Carolina Slate Belt and the Eastern Slate Belt were assigned a recharge rate of three hundred thousand gallons per day per square mile. Those sections of the county underlain by the Ashville Basin, Charlotte and/or Raleigh Belts were assigned a value of four hundred thousand gallons per day per square mile (Heath, 1994).

Data and Methodology Summation

Figure 5 summarizes the data preparation and analysis used in this study. The Microsoft ACCESS environment was used to query and prepare data for use within ArcGIS. Using techniques common to spatial analysis the data was analyzed to determine if known sites of groundwater contamination intersected the established wellhead protection areas. Zonal statistics were generated to determine whether or not land cover could be related to sites of known contamination. Zonal statistics were also used to determine the percentage of each block group occupying a given land use classification.

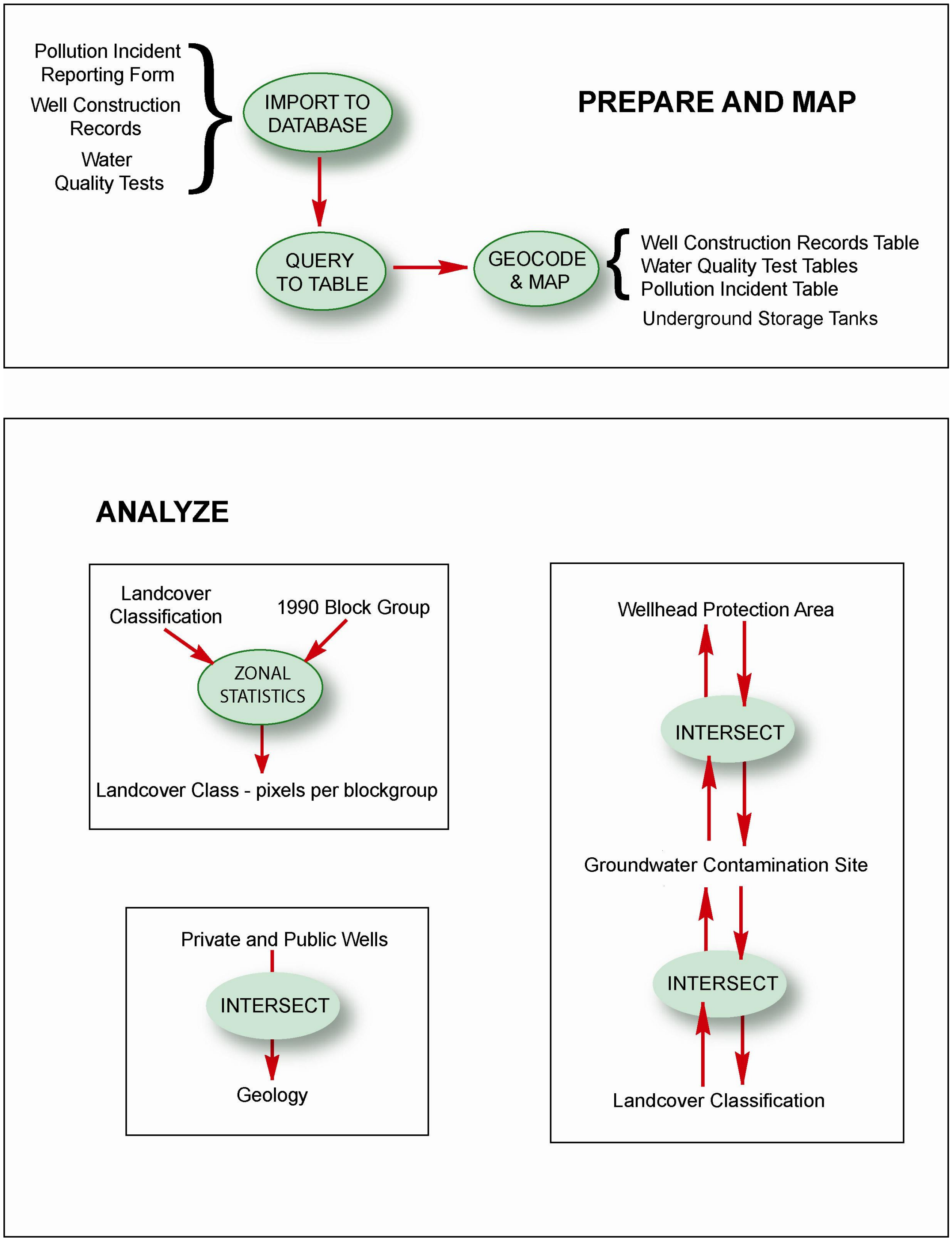


Figure 5. Methodology Flow Chart

CHAPTER IV

RESULTS

Based upon the 1990 census, of 107,706 households in Guilford County, 28,074 or 20 percent of households use groundwater wells as their primary water source. When this number is analyzed at the level of census block groups it revealed:

- private wells are the predominant source of water in unincorporated sections of the county (figure 6)
- the number of wells per square mile ranges from 0 to 171 (figure 7)
- areas within the city limits of Greensboro and Highpoint have the lowest number of wells per square mile

Thirty two percent of groundwater contamination incidents occurred in block groups where the land cover classification was one hundred percent dedicated to development. Seventy percent of all groundwater contamination incidents occurred in block groups containing between seventy and one hundred percent development (figure 8). The data clearly shows pollution incidents and groundwater contamination closing following development (figure 9).

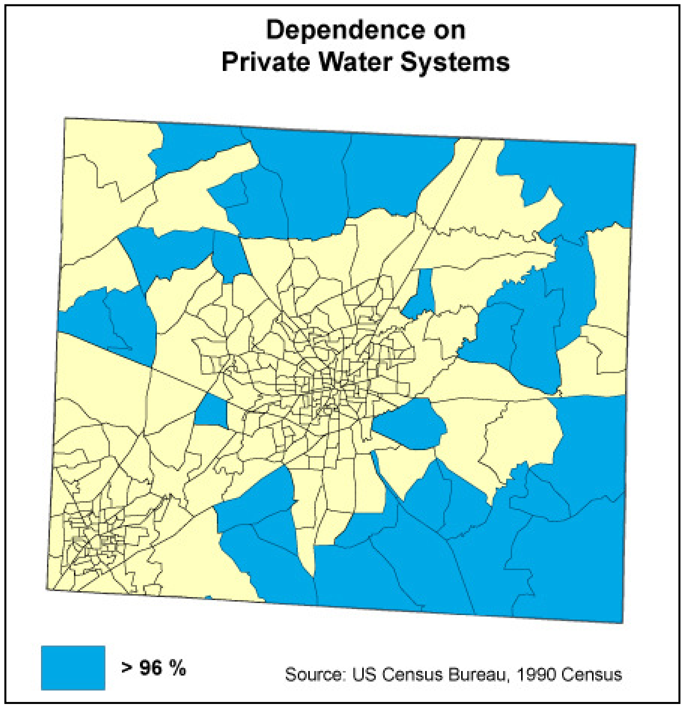


Figure 6. Private water supply

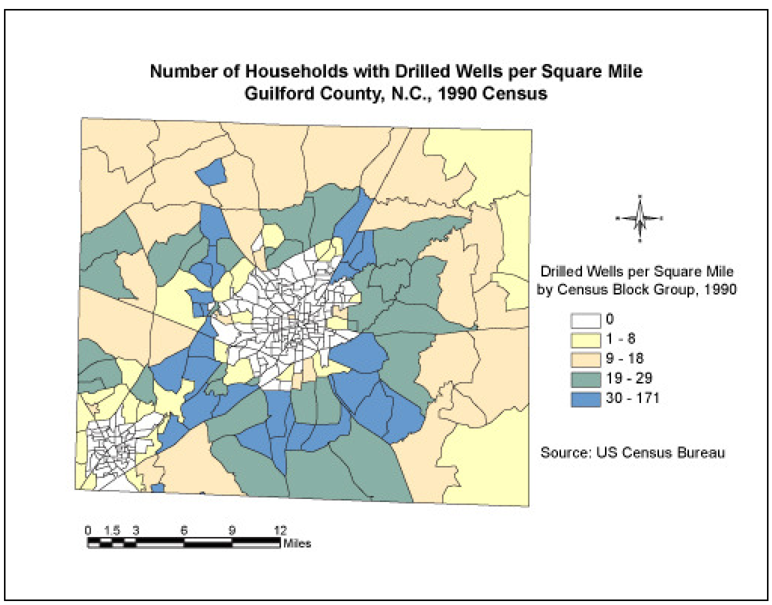


Figure 7. Wells per square mile

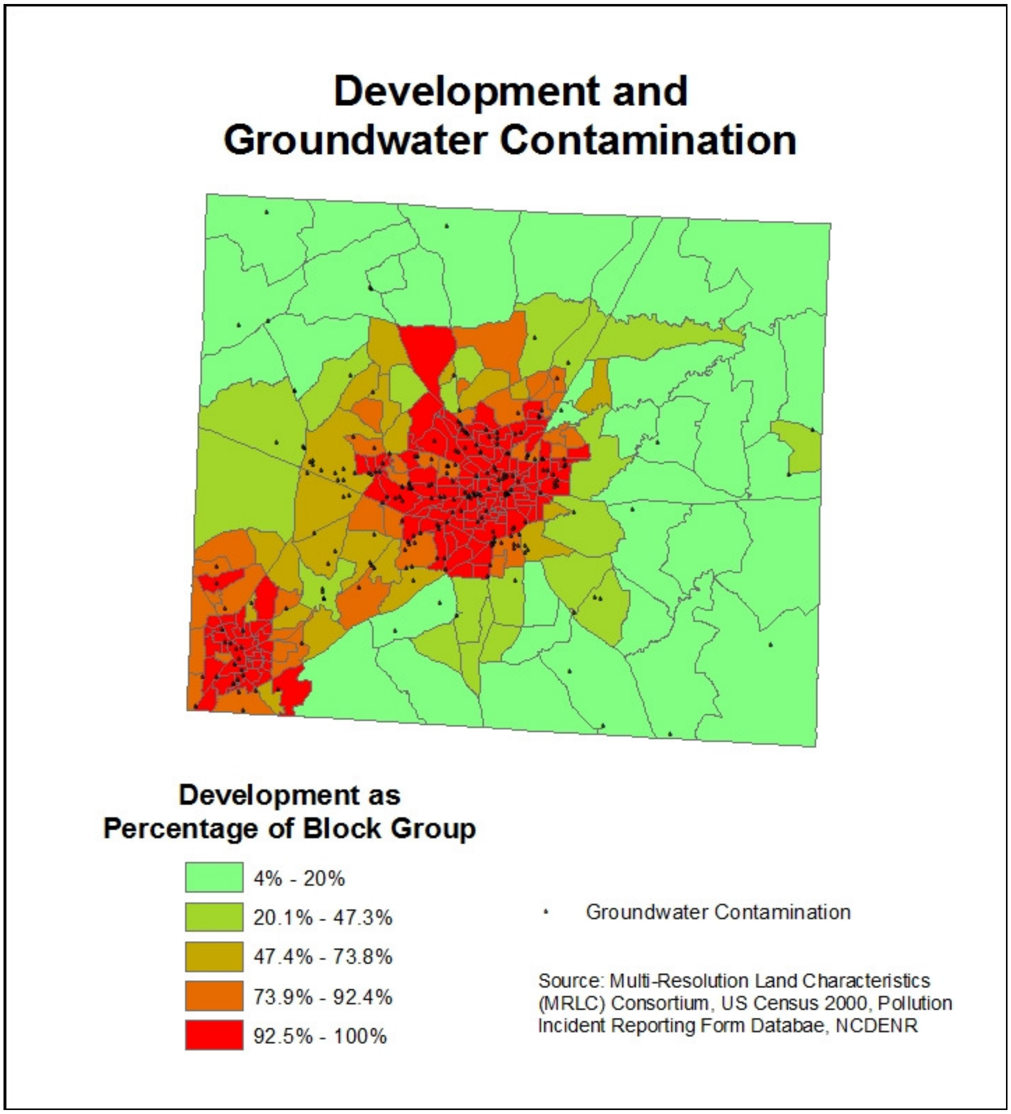


Figure 8. Development as percent of land cover and groundwater contamination sites

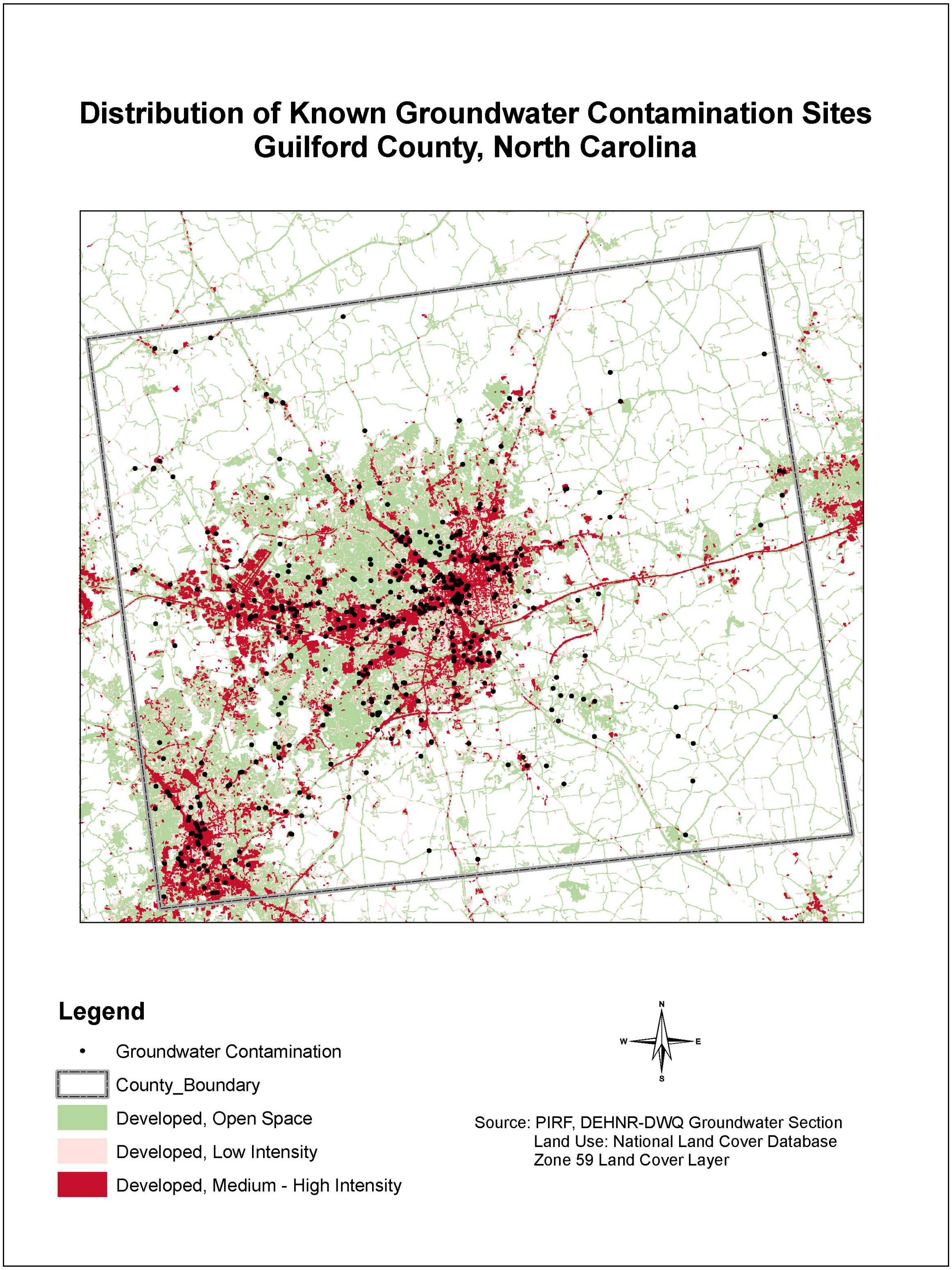


Figure 9. Groundwater contamination follows development

However the same cannot be said for wells. Of ninety five contaminated wells only 3 are located in block groups with a land cover classification of one hundred percent developed Only seven contaminated wells are located in block groups with a land cover classification of developed between seventy and one hundred percent. The majority of wells impacted by groundwater contamination are in block groups containing a land cover classification of developed for less then thirty percent of their total area. In addition only twenty five well head protection areas are intersected by pollution incidents known to have contaminated groundwater (figure 10). Well head protection buffers are shown in blue. Groundwater contamination sites which intersect the buffer are shown in red.

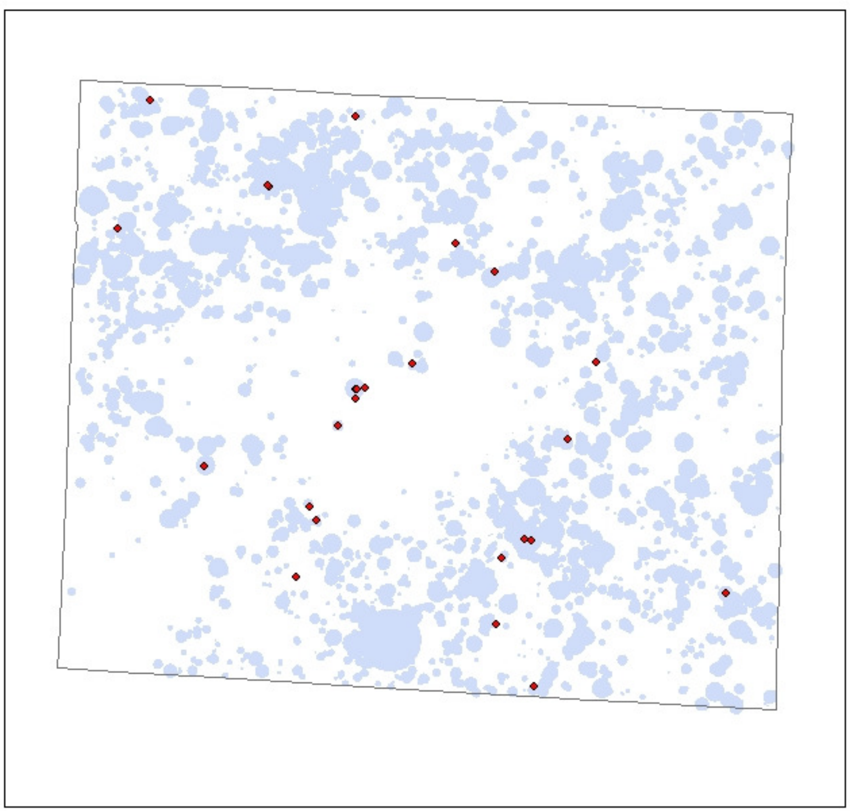


Figure 10. Wellhead buffers and contaminated groundwater

Based upon data used in this study the primary source of groundwater contamination in Guilford County is the result of leaking underground storage tanks followed by leaking heating oil tanks. The primary contaminants are Gasoline (233 reports), Heating Oil (66 reports), and Diesel Fuel (46 reports).

Inorganic Contaminants

Inorganic water quality test results were grouped based upon the geological setting of the well. An explanation of the table structure is found in table 5.

Column Heading	Definition
< LOQ	Test results are below a level with which they can be reported with a high degree of confidence.
Greater than LOQ	Results can be reported with a high degree of confidence
Geology	A code signifying the geologic age and unit in which the well was found.
Count	The number of water quality samples
LOQ	The concentration at which quantitative results can be reported with a high degree of confidence. This varies based upon the equipment used by the laboratory and the chemical being measured.
Minimum	The lowest value
Mean	The average value
Median	When values are ranked from low to high that occurring in the middle
Maximum	The highest value
Standard Deviation	measures the spread of data about the mean

Table 5. Definition of terms

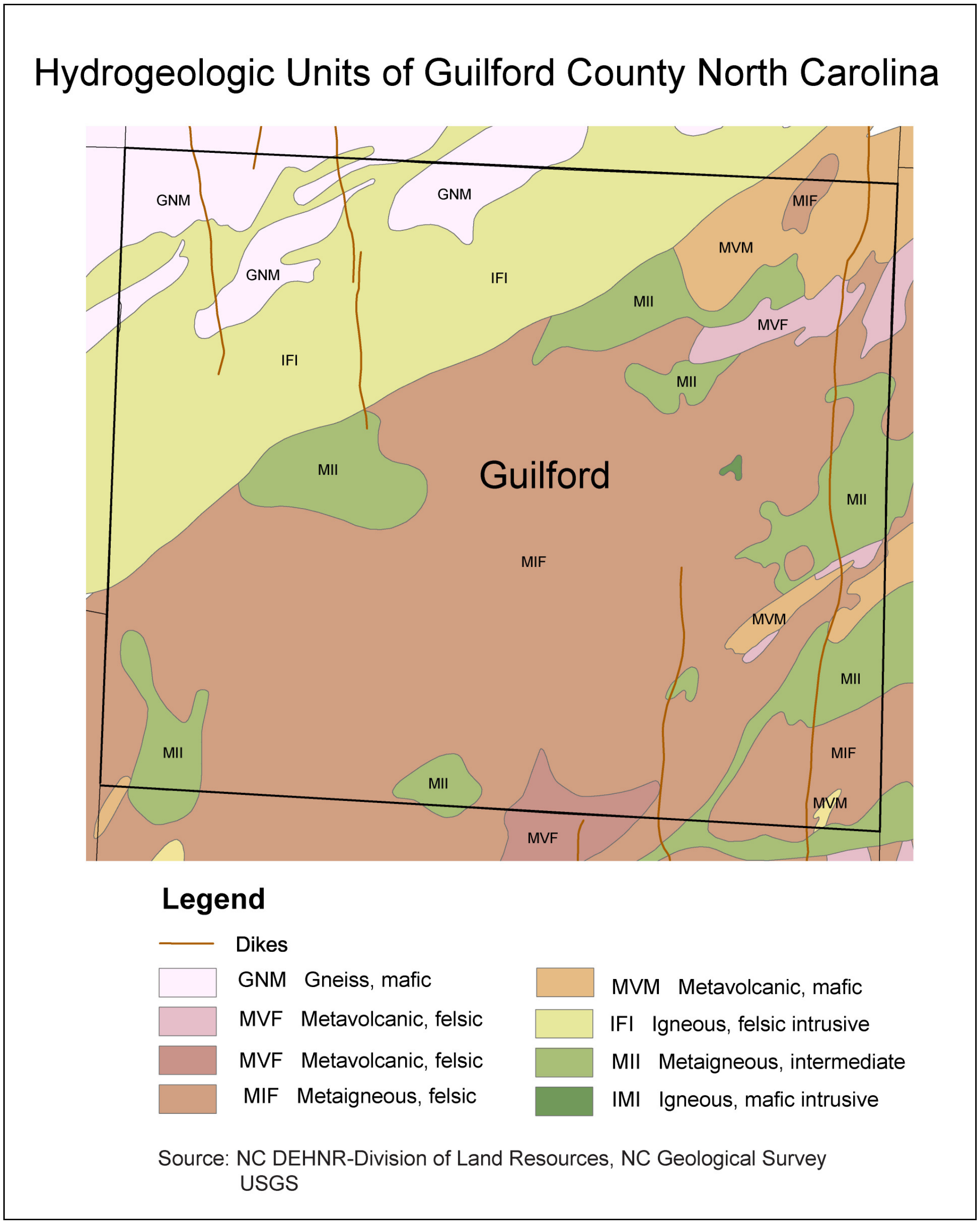


Figure 11. Hydrogeologic Units

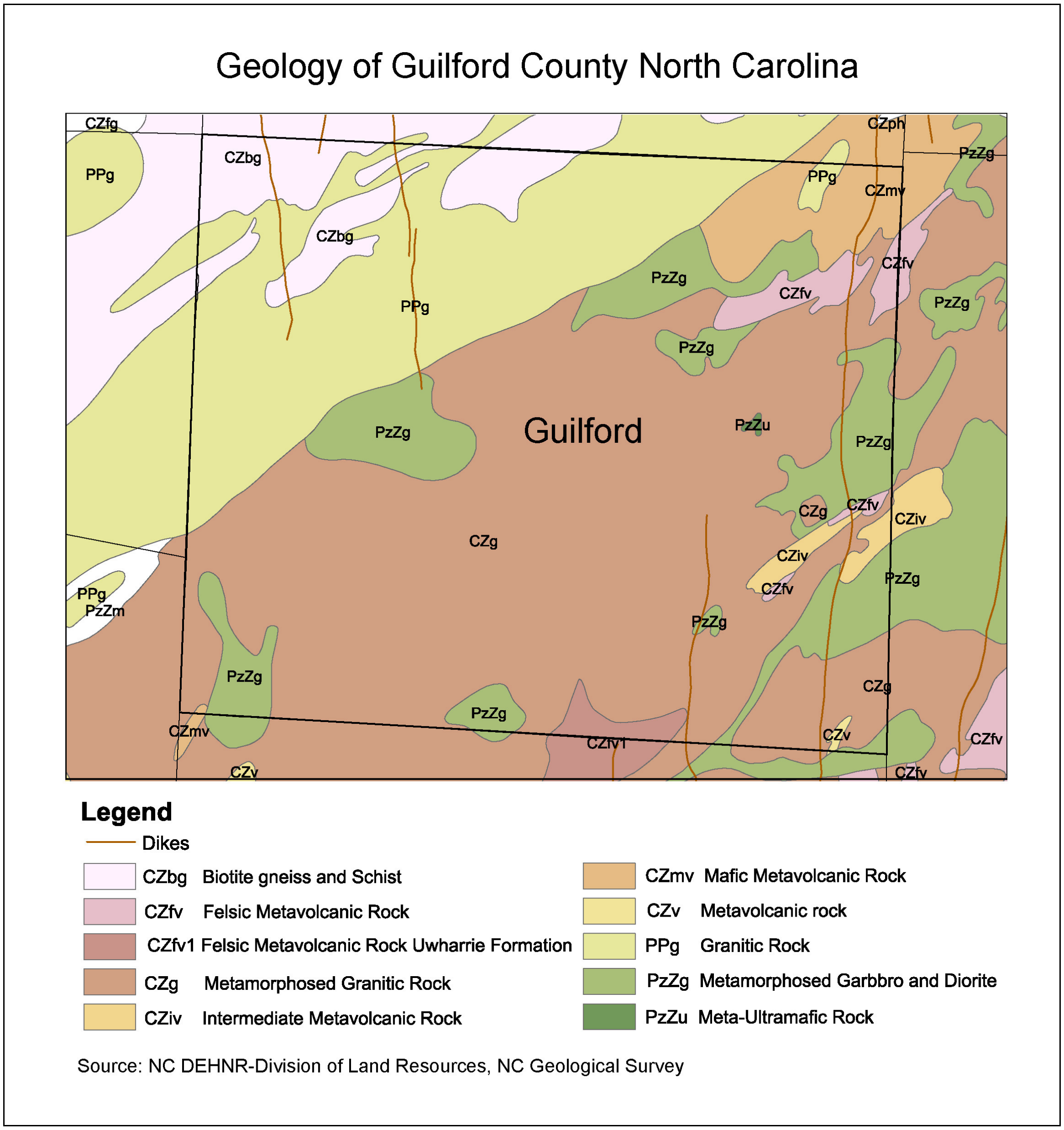


Figure 12. Geology of Guilford County

Arsenic

			< LOQ		Greater than LOQ					
	Geology	Total Count	LOQ	Count	Minimum	Mean	Median	Maximum	Standard deviation	Count
Arsenic	PPg	192	< 0.001	171	0.001	0.025	0.002	0.325	0.074	19
	PzZg	30	< 0.001	30	.	.	.	.	.	0
	CZbg	27	< 0.001	23	0.001	0.002	0.002	0.002	0.001	4
	CZmv	6	< 0.001	5	.	.	.	0.001	.	1
	Cziv	4	< 0.001	4	.	.	.	.	.	0
	CZfv	13	< 0.001	13	.	.	.	.	.	0
	CZfv1	4	< 0.001	4	.	.	.	.	.	0
	CZg	300	< 0.001	266	0.001	0.003	0.002	0.012	0.003	34

Table 6. Arsenic

Iron

The EPA and North Carolina secondary drinking water standard for iron is 0.3 mg/l. This is primarily for aesthetic reasons. Levels above 0.3mg/l may cause an orange-brown discoloration of laundry and water supply lines.

			< LOQ		Greater than LOQ					
	Geology	Total Count	LOQ	Count	Minimum	Mean	Median	Maximum	Standard deviation	Count
Iron	PPg	192	< 0.05	96	0.05	33.19	0.16	1908	199.64	96
	PzZg	30	< 0.05	12	0.05	6.69	0.24	65.64	18.7	18
	CZbg	27	< 0.05	21	0.05	1.48	**0.46**	5.88	2.27	6
	CZmv	6	< 0.05	1	0.05	161	0.18	803.5	359	5
	Cziv	4	< 0.05	0	0.08	4	1	16.79	8	4
	CZfv	13	< 0.05	4	0.05	4.07	**0.49**	14.2	5.93	9
	CZfv1	4	< 0.05	1	0.11	0.41	0.24	0.88	0.41	3
	CZg	300	< 0.05	118	0.05	35.3	**0.43**	1427	135.48	182

Table 7. Iron

Copper

The primary source of copper in drinking water is the corrosion of copper pipes and fittings. North Carolina limits copper in drinking water to 1.0 mg/l. Of 576 samples, 4 exceed North Carolina drinking water limits. Two were found in the PPg and 2 in the CZg geologic unit.

			< LOQ		Greater than LOQ					
	Geology	Total Count	LOQ	Count	Minimum	Mean	Median	Maximum	Standard Deviation	Count
Copper	PPg	192	< 0.05	148	0.05	4.31	0.32	4.31	0.69	44
	PzZg	30	< 0.05	25	0.05	0.154	0.17	0.26	0.081	5
	CZbg	27	< 0.05	22	0.09	0.17	0.1	0.43	0.15	5
	CZmv	6	< 0.05	5	.	.	.	0.001	.	1
	Cziv	4	< 0.05	4	.	.	.	.	.	0
	CZfv	13	< 0.05	13	.	.	.	.	.	0
	CZfv1	4	< 0.05	4	.	.	.	.	.	0
	CZg	300	< 0.05	238	0.05	0.22	0.14	1.24	0.23	62

Table 8. Copper

Manganese

The EPA Secondary Standard for manganese is 0.05 mg/l. The median value for manganese in all geologic units with the exception of CZiv, CZfv1, and CZmv exceeds this level.

			< LOQ		Greater than LOQ					
	Geology	Total Count	LOQ	Count	Minimum	Mean	Median	Maximum	Standard deviation	Count
Manganese	PPg	192	< 0.03	162	0.03	0.59	0.1	13.1	2.37	30
	PzZg	30	< 0.03	20	0.05	0.24	0.24	0.41	0.13	10
	CZbg	27	< 0.03	24	0.13	0.62	0.66	1.08	0.48	3
	CZmv	6	< 0.03	1	0.04	0.72	0.04	3.42	1.51	5
	Cziv	4	< 0.03	3	.	.	.	.	0.14	1
	CZfv	13	< 0.03	9	0.04	0.45	0.14	1.49	0.69	4
	CZfv1	4	< 0.03	4	.	.	.	.	.	0
	CZg	300	< 0.03	184	0.03	1.08	0.175	46.3	4.87	116

Table 9. Manganese

Alkalinity

30-100 mg/l, as $CaCO_3$ is considered desirable to prevent serious corrosion of water supply lines. Alkalinity in water reflects its ability to neutralize acids.

	Geology	Count	Minimum	Mean	Median	Maximum	Standard deviation
Alkalinity	PPg	191	4.0	53.0	46.0	180.0	30.0
	PzZg	30	22	97	67	330	83
	CZbg	27	8	57	56	94	22
	CZmv	6	6.2	109	101	176	45
	Cziv	4	30	57	55	90	28
	CZfv	13	36	67	60	116	27
	CZfv1	4	44	72	68	106	26
	CZg	300	18	96	77	390	65

Table 10. Alkalinity

Calcium

There are no drinking water standards for calcium and its presence in groundwater is considered to be desirable. The highest values were found in the PPg and the CZg geologic units.

	Geology	Count	Minimum	Mean	**Median**	Maximum	Standard deviation
Calcium	PPg	192	0	10.1	17.4	276.2	28.7
	PzZg	30	4.1	20.2	12.2	61.6	16.2
	CZbg	27	0	15.7	13.1	49	11.9
	CZmv	6	16.7	32.6	30.3	54.5	14.4
	Cziv	4	6	10.8	7.9	21.5	7.3
	CZfv	13	5.2	13.9	11.1	29.3	8.7
	CZfv1	4	1.3	7.5	8.3	12.1	4.6
	CZg	300	0	27	15.7	1218	71.8

Table 11. Calcium

Magnesium

There are no primary or secondary standards for magnesium in drinking water. The presence of magnesium in water is beneficial and no limits have been set for human or aquatic health (Weiner).

	Geology	Count	Minimum	Mean	Median	Maximum	Standard deviation
Magnesium	PPg	192	0	3.5	3.2	13.1	2.2
	PzZg	30	1.5	8	5.5	42.8	8.8
	CZbg	27	0	2.9	2.8	6.5	1.4
	CZmv	6	4.5	7.7	8.4	10.3	2.6
	Cziv	4	2.5	4.8	4.4	6	2.6
	CZfv	13	3	13.3	6.1	5.3	2.9
	CZfv1	4	0.5	3.7	3.9	6.3	2.4
	CZg	300	0	7.8	5.7	47.1	10.2

Table 12. Magnesium

Hydrogen-ion Concentration (pH)

Water with a pH above 7 is considered basic and that below 7 acidic. The recommended pH level for drinking water is not less than 6.5. Water which is acidic can have a corrosive effect on water supply lines and sewage systems (DPHEHD).

	Geology	Count	Minimum	Mean	Median	Maximum	Standard deviation
pH	PPg	191	5.6	7	6.9	8.8	0.9
	PzZg	30	6.3	7.1	7.0	8.0	0.6
	CZbg	27	6.0	7.1	7.1	8.2	0.6
	CZmv	6	6.5	7.4	7.6	8.1	0.6
	Cziv	4	6.8	7.4	7.0	8.8	
	CZfv	13	6.5	7.0	7.0	7.8	0.0
	CZfv1	4	6.4	6.9	6.9	7.2	0.4
	CZg	300	6.0	7.1	7.0	10.6	0.6

Table 13. Hydrogen-ion Concentration (pH)

CHAPTER V

DISCUSSION

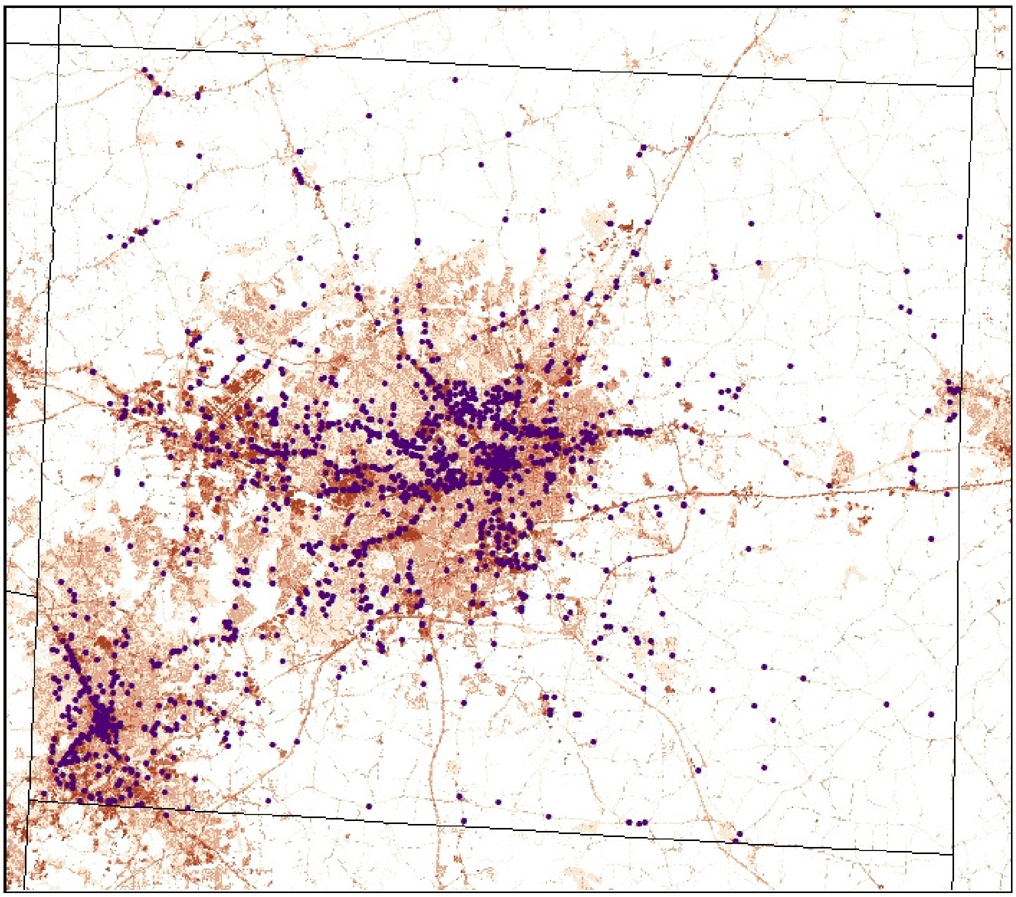


Figure 13. Pollution incidents and development

Based upon currently available data the primary source of groundwater contamination in Guilford County is from leaking underground storage tanks. Gasoline, heating oil and diesel fuel are the most common contaminants. While pollution incidents are highest within areas with a land cover classification of developed (figure 13), their impact on drinking water wells is low. This can be explained by the distribution of wells within the county. The majority of wells used for drinking water are located in rural sparsely developed regions. While the impact of groundwater contamination on the population of Guilford County is currently low, it does present a serious problem. As the population continues to increase, and with it the demand for water, groundwater contamination can become a limiting factor.

Because the primary source of contamination is from leaking underground storage tanks many of the assumptions made on vulnerability do not hold true. For example, the majority of groundwater contamination incidents have occurred in areas with high levels of impervious services. In studies of vulnerability using index and overlay methods impervious services were said to reduce vulnerability. With leaking underground storage tanks contamination enters the system not from the surface but from two feet to more than fifteen feet below ground.

In this study the pollution incident report database proved to be the most helpful in mapping the distribution of groundwater contamination incidents. This database is a working document and as such has many errors. Errors of omission were the most frequently encountered. For example, a site may have no data listed in the column indicating groundwater contamination, yet in the description it will say that groundwater contamination was above 2 liter standards. Before using the data it should be checked to assure consistency. Another problem encountered was the lack of or missing latitude and longitude values. While data could be mapped by geocoding, based upon an address, it does not give you an exact location. The point generated is an estimated location.

Many of the points generated by address matching were more then five hundred feet from the actual location. This was more likely with properties located on state highways that run through rural sections of the county than in urban regions. Geocoding based upon parcels would place the point on the correct property but again is an estimated location. Problems related to location can be solved by making the collection of latitude and longitude a standard part of data collection efforts.

Most importantly it must be noted that the data are only showing us ‘a picture in time’. The information is true at the time it was collected. Contaminates in the aquifer are not static. A well found to be free of contamination may test positive for contaminates at a future point in time. Similarly a well reported as containing high levels of a specific contaminate can in future tests see those values decline.

Much can be learned form studies incorporating publicly available data. This information can be used not only to inform the public of hazards within their community but to reassure them that efforts are being made to assure their safety and the health of the environment. It is an awareness of problems with leaking underground storage tanks that led to improvements in their design. An awareness of the fragility of the aquifers underlying our feet could lead to an increased effort to protect them from manmade contaminates.

CHAPTER VI

CONCLUSION

The data available for this study is strongly biased toward point sources of contamination. The pollution incidents listed in the PIRF database occur in fixed locations and are related to spills and leaks in manmade structures; as a result, when mapped (figure 13) these incidents closely follow areas of development. Reports of contamination in private wells from non-point sources were low. This may be due to a lack of data rather than an absence of contamination.

Newly constructed wells are tested for nitrates and bacteria; testing for pesticides and VOC contamination is only performed at the request of the homeowner or as a result of an ancillary event at the request of a government agency. It is very likely that this initial testing is the only testing a private well will receive. This presents an obstacle in assessing the impact of non-point sources of contamination on private wells and leaves the well user vulnerable to the effect of contaminants which may be present.

The results of this thesis show GIS to be useful in the study of groundwater contamination and confirm the need for regular water quality testing of private wells. Analysis revealed point sources of contamination such as leaking underground storage tanks to be the primary source of groundwater contamination in Guilford Country. Gasoline, heating oil and diesel fuel were the major contaminates. Although counter intuitive, as the impervious surface area increased, so did the incidents of groundwater contamination.

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APPENDIX A

SUMMARY STATISTICS

Relationship between developed land cover classification and groundwater contamination incidents

Block Group	Developed	Sites with Groundwater Contamination	Running Site Count	Running Percent of Total	Wells Impacted	Well Impact Running Count
370810108011	100.000%	43.000	43.000	6.53%	2	2
370810146001	100.000%	20.000	63.000	9.56%	0	2
370810110001	100.000%	11.000	74.000	11.23%	0	2
370810114001	100.000%	9.000	83.000	12.59%	0	2
370810107011	100.000%	7.000	90.000	13.66%	0	2
370810116021	100.000%	7.000	97.000	14.72%	0	2
370810126011	100.000%	7.000	104.000	15.78%	1	3
370810143004	100.000%	6.000	110.000	16.69%	0	3
370810110003	100.000%	5.000	115.000	17.45%	0	3
370810116011	100.000%	5.000	120.000	18.21%	0	3
370810125082	100.000%	5.000	125.000	18.97%	0	3
370810104012	100.000%	4.000	129.000	19.58%	0	3
370810110002	100.000%	4.000	133.000	20.18%	0	3
370810112005	100.000%	4.000	137.000	20.79%	0	3
370810115001	100.000%	4.000	141.000	21.40%	0	3
370810125083	100.000%	4.000	145.000	22.00%	0	3
370810101001	100.000%	3.000	148.000	22.46%	0	3
370810102003	100.000%	3.000	151.000	22.91%	0	3
370810104042	100.000%	3.000	154.000	23.37%	0	3
370810107021	100.000%	3.000	157.000	23.82%	0	3
370810107023	100.000%	3.000	160.000	24.28%	0	3
370810114003	100.000%	3.000	163.000	24.73%	0	3
370810106012	100.000%	2.000	165.000	25.04%	0	3
370810106021	100.000%	2.000	167.000	25.34%	0	3
370810106023	100.000%	2.000	169.000	25.64%	0	3
370810106024	100.000%	2.000	171.000	25.95%	0	3
370810112004	100.000%	2.000	173.000	26.25%	0	3
370810113003	100.000%	2.000	175.000	26.56%	0	3
370810113004	100.000%	2.000	177.000	26.86%	0	3
370810115002	100.000%	2.000	179.000	27.16%	0	3
370810116022	100.000%	2.000	181.000	27.47%	0	3
370810125081	100.000%	2.000	183.000	27.77%	0	3
370810127042	100.000%	2.000	185.000	28.07%	0	3
370810136022	100.000%	2.000	187.000	28.38%	0	3
370810136023	100.000%	2.000	189.000	28.68%	0	3

370810138004	100.000%	2.000	191.000	28.98%	0	3
370810104032	100.000%	1.000	192.000	29.14%	0	3
370810105001	100.000%	1.000	193.000	29.29%	0	3
370810105002	100.000%	1.000	194.000	29.44%	0	3
370810105003	100.000%	1.000	195.000	29.59%	0	3
370810106011	100.000%	1.000	196.000	29.74%	0	3
370810106022	100.000%	1.000	197.000	29.89%	0	3
370810107022	100.000%	1.000	198.000	30.05%	0	3
370810109002	100.000%	1.000	199.000	30.20%	0	3
370810111011	100.000%	1.000	200.000	30.35%	0	3
370810112001	100.000%	1.000	201.000	30.50%	0	3
370810113001	100.000%	1.000	202.000	30.65%	0	3
370810115003	100.000%	1.000	203.000	30.80%	0	3
370810126042	100.000%	1.000	204.000	30.96%	0	3
370810126102	100.000%	1.000	205.000	31.11%	0	3
370810127041	100.000%	1.000	206.000	31.26%	0	3
370810136012	100.000%	1.000	207.000	31.41%	0	3
370810136021	100.000%	1.000	208.000	31.56%	0	3
370810136024	100.000%	1.000	209.000	31.71%	0	3
370810137002	100.000%	1.000	210.000	31.87%	0	3
370810140001	100.000%	1.000	211.000	32.02%	0	3
370810142003	100.000%	1.000	212.000	32.17%	0	3
370810142005	100.000%	1.000	213.000	32.32%	0	3
370810161023	100.000%	1.000	214.000	32.47%	0	3
370810161026	100.000%	1.000	215.000	32.63%	0	3
370810107012	100.000%	0.000	215.000	32.63%	0	3
370810109001	100.000%	0.000	215.000	32.63%	0	3
370810112002	100.000%	0.000	215.000	32.63%	0	3
370810112003	100.000%	0.000	215.000	32.63%	0	3
370810114002	100.000%	0.000	215.000	32.63%	0	3
370810114004	100.000%	0.000	215.000	32.63%	0	3
370810114005	100.000%	0.000	215.000	32.63%	0	3
370810114006	100.000%	0.000	215.000	32.63%	0	3
370810115004	100.000%	0.000	215.000	32.63%	0	3
370810127061	100.000%	0.000	215.000	32.63%	0	3
370810137001	100.000%	0.000	215.000	32.63%	0	3
370810137003	100.000%	0.000	215.000	32.63%	0	3
370810137004	100.000%	0.000	215.000	32.63%	0	3
370810138001	100.000%	0.000	215.000	32.63%	0	3
370810138003	100.000%	0.000	215.000	32.63%	0	3
370810139001	100.000%	0.000	215.000	32.63%	0	3
370810139002	100.000%	0.000	215.000	32.63%	0	3
370810139003	100.000%	0.000	215.000	32.63%	0	3
370810139004	100.000%	0.000	215.000	32.63%	0	3
370810142001	100.000%	0.000	215.000	32.63%	0	3
370810142002	100.000%	0.000	215.000	32.63%	0	3
370810142004	100.000%	0.000	215.000	32.63%	0	3
370810143001	100.000%	0.000	215.000	32.63%	0	3
370810144022	100.000%	0.000	215.000	32.63%	0	3

370810104011	99.871%	1.000	216.000	32.78%	0	3
370810125051	99.809%	4.000	220.000	33.38%	0	3
370810126101	99.771%	0.000	220.000	33.38%	0	3
370810108021	99.759%	7.000	227.000	34.45%	0	3
370810126171	99.675%	2.000	229.000	34.75%	0	3
370810127071	99.659%	5.000	234.000	35.51%	0	3
370810104041	99.584%	2.000	236.000	35.81%	0	3
370810126081	99.519%	6.000	242.000	36.72%	0	3
370810116023	99.487%	1.000	243.000	36.87%	0	3
370810138002	99.454%	1.000	244.000	37.03%	0	3
370810116012	99.442%	0.000	244.000	37.03%	0	3
370810125091	99.421%	6.000	250.000	37.94%	0	3
370810143002	99.410%	0.000	250.000	37.94%	0	3
370810144053	99.278%	1.000	251.000	38.09%	0	3
370810161024	99.274%	5.000	256.000	38.85%	0	3
370810127072	99.268%	5.000	261.000	39.61%	0	3
370810126043	99.253%	0.000	261.000	39.61%	0	3
370810125084	99.172%	0.000	261.000	39.61%	0	3
370810143003	99.144%	7.000	268.000	40.67%	0	3
370810136011	99.124%	0.000	268.000	40.67%	0	3
370810126121	98.947%	5.000	273.000	41.43%	0	3
370810125041	98.911%	2.000	275.000	41.73%	0	3
370810126091	98.911%	5.000	280.000	42.49%	0	3
370810126112	98.728%	1.000	281.000	42.64%	0	3
370810125032	98.712%	0.000	281.000	42.64%	0	3
370810125062	98.425%	2.000	283.000	42.94%	0	3
370810126123	98.287%	1.000	284.000	43.10%	0	3
370810137005	98.231%	0.000	284.000	43.10%	0	3
370810111021	98.190%	0.000	284.000	43.10%	0	3
370810126013	98.170%	18.000	302.000	45.83%	0	3
370810145011	98.159%	10.000	312.000	47.34%	0	3
370810113002	98.090%	5.000	317.000	48.10%	0	3
370810104043	97.883%	2.000	319.000	48.41%	0	3
370810125063	97.872%	0.000	319.000	48.41%	0	3
370810126111	97.812%	0.000	319.000	48.41%	0	3
370810103002	97.193%	12.000	331.000	50.23%	0	3
370810161027	97.153%	7.000	338.000	51.29%	1	4
370810161025	96.960%	0.000	338.000	51.29%	0	4
370810116013	96.953%	1.000	339.000	51.44%	0	4
370810126012	96.747%	8.000	347.000	52.66%	0	4
370810102001	96.629%	0.000	347.000	52.66%	0	4
370810104031	96.287%	6.000	353.000	53.57%	0	4
370810126041	95.447%	5.000	358.000	54.32%	0	4
370810102002	95.397%	2.000	360.000	54.63%	0	4
370810126122	95.086%	2.000	362.000	54.93%	0	4
370810160045	94.950%	1.000	363.000	55.08%	0	4
370810125061	94.771%	0.000	363.000	55.08%	0	4
370810111012	94.723%	6.000	369.000	55.99%	0	4
370810145022	94.290%	3.000	372.000	56.45%	0	4

370810157012	93.849%	0.000	372.000	56.45%	0	4
370810144023	92.432%	1.000	373.000	56.60%	0	4
370810145012	92.257%	1.000	374.000	56.75%	0	4
370810145032	91.819%	1.000	375.000	56.90%	0	4
370810125053	91.771%	1.000	376.000	57.06%	0	4
370810128042	91.348%	2.000	378.000	57.36%	0	4
370810127052	90.999%	0.000	378.000	57.36%	0	4
370810103001	90.517%	0.000	378.000	57.36%	0	4
370810140002	90.501%	4.000	382.000	57.97%	0	4
370810119051	90.305%	0.000	382.000	57.97%	0	4
370810161022	89.523%	2.000	384.000	58.27%	0	4
370810161021	89.379%	0.000	384.000	58.27%	0	4
370810125052	89.050%	2.000	386.000	58.57%	0	4
370810127031	89.014%	1.000	387.000	58.73%	0	4
370810161012	88.491%	3.000	390.000	59.18%	0	4
370810128041	88.464%	9.000	399.000	60.55%	0	4
370810144072	88.060%	2.000	401.000	60.85%	0	4
370810125031	88.021%	0.000	401.000	60.85%	0	4
370810127043	87.823%	0.000	401.000	60.85%	0	4
370810126092	87.110%	4.000	405.000	61.46%	0	4
370810144052	86.688%	1.000	406.000	61.61%	0	4
370810119053	85.343%	1.000	407.000	61.76%	0	4
370810157023	85.064%	0.000	407.000	61.76%	0	4
370810119042	84.763%	0.000	407.000	61.76%	0	4
370810126071	84.628%	0.000	407.000	61.76%	0	4
370810163011	83.800%	1.000	408.000	61.91%	0	4
370810127062	83.530%	1.000	409.000	62.06%	0	4
370810165031	82.821%	1.000	410.000	62.22%	0	4
370810157022	81.592%	0.000	410.000	62.22%	0	4
370810144021	81.552%	2.000	412.000	62.52%	0	4
370810163012	81.000%	0.000	412.000	62.52%	0	4
370810160044	80.845%	42.000	454.000	68.89%	2	6
370810165021	80.643%	2.000	456.000	69.20%	1	7
370810144061	79.571%	1.000	457.000	69.35%	0	7
370810119052	79.436%	0.000	457.000	69.35%	0	7
370810127051	79.026%	1.000	458.000	69.50%	0	7
370810144071	77.358%	4.000	462.000	70.11%	0	7
370810145031	76.385%	3.000	465.000	70.56%	0	7
370810144081	75.210%	0.000	465.000	70.56%	0	7
370810165022	73.775%	8.000	473.000	71.78%	0	7
370810157031	72.857%	2.000	475.000	72.08%	0	7
370810144051	69.501%	3.000	478.000	72.53%	0	7
370810160042	69.312%	1.000	479.000	72.69%	0	7
370810161011	68.733%	0.000	479.000	72.69%	0	7
370810165041	67.794%	2.000	481.000	72.99%	1	8
370810163021	67.791%	1.000	482.000	73.14%	0	8
370810119041	67.614%	0.000	482.000	73.14%	0	8
370810164031	67.252%	15.000	497.000	75.42%	1	9
370810144062	66.957%	0.000	497.000	75.42%	0	9

370810145021	66.608%	1.000	498.000	75.57%	0	9
370810111022	65.847%	1.000	499.000	75.72%	0	9
370810164041	64.769%	3.000	502.000	76.18%	2	11
370810160022	64.437%	0.000	502.000	76.18%	0	11
370810154001	63.936%	3.000	505.000	76.63%	0	11
370810160023	58.852%	0.000	505.000	76.63%	0	11
370810165023	57.423%	2.000	507.000	76.93%	1	12
370810160043	56.413%	0.000	507.000	76.93%	0	12
370810164022	55.975%	2.000	509.000	77.24%	1	13
370810157013	55.339%	1.000	510.000	77.39%	0	13
370810128051	54.593%	9.000	519.000	78.76%	0	13
370810163022	53.103%	1.000	520.000	78.91%	1	14
370810164021	47.303%	12.000	532.000	80.73%	0	14
370810160041	46.095%	3.000	535.000	81.18%	0	14
370810154002	39.198%	0.000	535.000	81.18%	0	14
370810155002	36.743%	2.000	537.000	81.49%	0	14
370810167002	36.456%	2.000	539.000	81.79%	0	14
370810162012	35.278%	5.000	544.000	82.55%	4	18
370810157021	34.350%	2.000	546.000	82.85%	0	18
370810157011	34.120%	4.000	550.000	83.46%	0	18
370810128032	32.964%	2.000	552.000	83.76%	0	18
370810128031	32.464%	2.000	554.000	84.07%	3	21
370810167001	31.823%	6.000	560.000	84.98%	2	23
370810160021	30.530%	3.000	563.000	85.43%	0	23
370810168002	29.484%	3.000	566.000	85.89%	0	23
370810171002	28.218%	6.000	572.000	86.80%	2	25
370810152002	28.074%	1.000	573.000	86.95%	0	25
370810162021	27.673%	2.000	575.000	87.25%	0	25
370810171001	27.231%	5.000	580.000	88.01%	1	26
370810167003	25.602%	2.000	582.000	88.32%	0	26
370810168004	23.892%	2.000	584.000	88.62%	0	26
370810155001	23.824%	3.000	587.000	89.07%	0	26
370810153003	20.010%	0.000	587.000	89.07%	0	26
370810168001	19.912%	0.000	587.000	89.07%	0	26
370810166001	19.289%	5.000	592.000	89.83%	2	28
370810168003	19.078%	0.000	592.000	89.83%	0	28
370810167004	18.303%	0.000	592.000	89.83%	0	28
370810158002	17.531%	5.000	597.000	90.59%	1	29
370810160031	16.290%	3.000	600.000	91.05%	0	29
370810154003	15.000%	0.000	600.000	91.05%	0	29
370810152003	14.476%	5.000	605.000	91.81%	26	55
370810172001	13.799%	2.000	607.000	92.11%	0	55
370810156003	13.327%	1.000	608.000	92.26%	0	55
370810154006	13.261%	3.000	611.000	92.72%	1	56
370810153001	12.284%	0.000	611.000	92.72%	2	58
370810171003	12.086%	0.000	611.000	92.72%	0	58
370810159002	12.050%	10.000	621.000	94.23%	7	65
370810154005	11.876%	0.000	621.000	94.23%	0	65
370810154004	11.684%	3.000	624.000	94.69%	0	65

370810153002	11.130%	3.000	627.000	95.14%	3	68
370810162011	11.115%	0.000	627.000	95.14%	0	68
370810169001	9.898%	9.000	636.000	96.51%	4	72
370810159003	9.778%	1.000	637.000	96.66%	9	81
370810167005	9.441%	1.000	638.000	96.81%	0	81
370810152001	8.830%	5.000	643.000	97.57%	1	82
370810170001	8.472%	5.000	648.000	98.33%	1	83
370810158001	8.394%	3.000	651.000	98.79%	5	88
370810158003	8.293%	1.000	652.000	98.94%	0	88
370810169002	8.223%	0.000	652.000	98.94%	0	88
370810172003	8.171%	0.000	652.000	98.94%	0	88
370810172002	6.993%	0.000	652.000	98.94%	0	88
370810159001	6.724%	5.000	657.000	99.70%	7	95
370810151002	6.255%	1.000	658.000	99.85%	0	95
370810152004	5.482%	0.000	658.000	99.85%	0	95
370810170002	5.312%	1.000	659.000	100.00%	0	95
370810156002	5.306%	0.000	659.000	100.00%	0	95
370810151001	4.156%	0.000	659.000	100.00%	0	95
370810156001	3.967%	0.000	659.000	100.00%	0	95

APPENDIX B

LAND COVER CLASSIFICATION

Definition of Land Cover Classes Containing a Reported Pollution Incidence

Domain Value: 21 Definition: **Developed, Open Space**
Includes areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.

Domain Value: 22 Definition: **Developed, Low Intensity**
Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20-49 percent of total cover. These areas most commonly include single-family housing units.

Domain Value: 23 Definition: **Developed, Medium Intensity**
Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50-79 percent of the total cover. These areas most commonly include single-family housing units.

Domain Value: 24 Definition: **Developed, High Intensity**
Includes highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to100 percent of the total cover.

Domain Value: 41 Definition: **Deciduous Forest**
Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75 percent of the tree species shed foliage simultaneously in response to seasonal change.

Domain Value: 42 Definition: **Evergreen Forest**
Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75 percent of the tree species maintain their leaves all year. Canopy is never without green foliage.

Domain Value: 81 Definition: **Pasture/Hay**
Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20 percent of total vegetation.

Domain Value: 82 Definition: **Cultivated Crops**
Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20 percent of total vegetation. This class also includes all land being actively tilled.

Domain Value Definition Source: NLCD 2001 landcover class descriptions

APPENDIX C

ADDITIONAL FIGURES

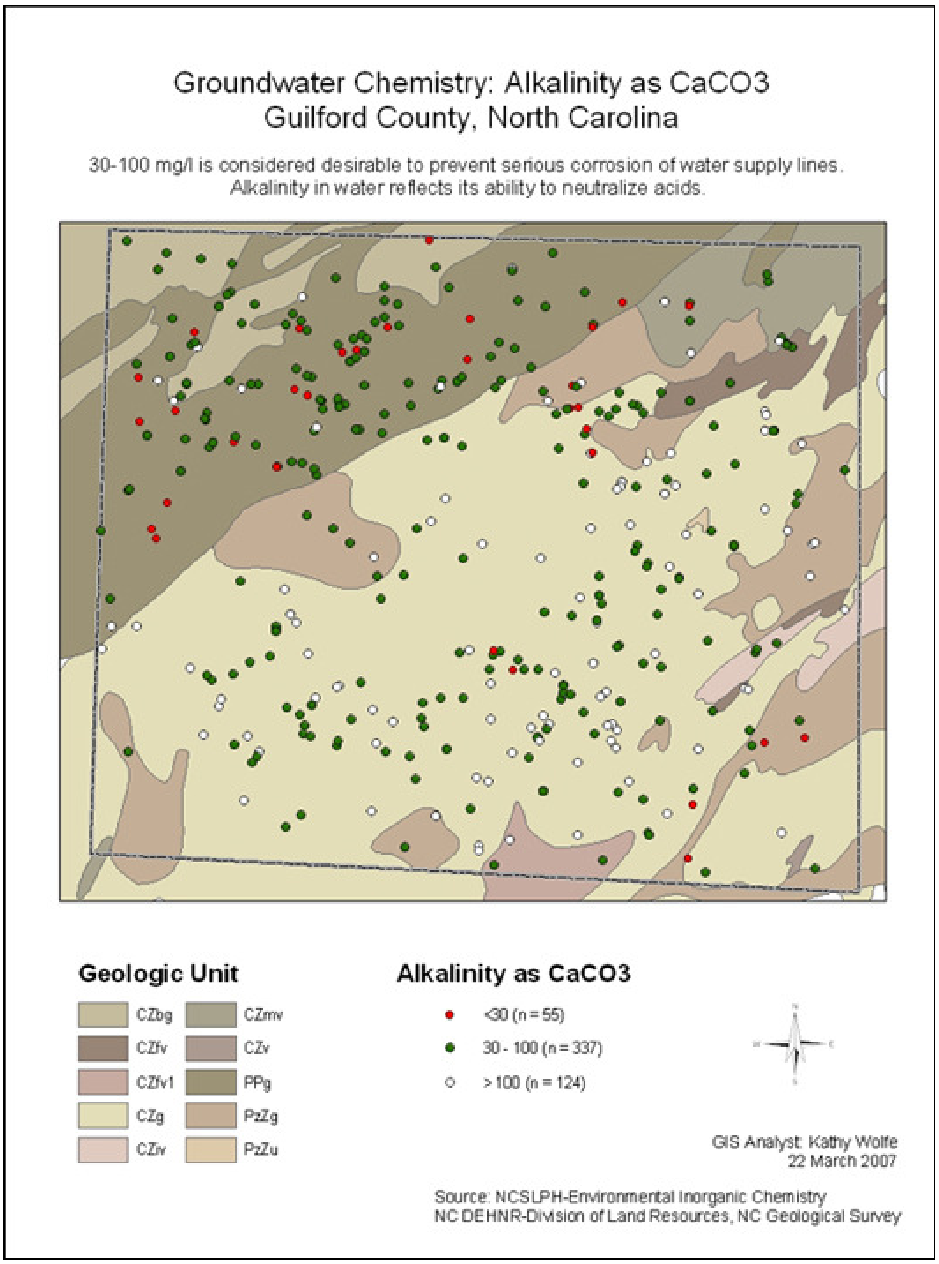

Figure 14. Alkalinity as CaCO3

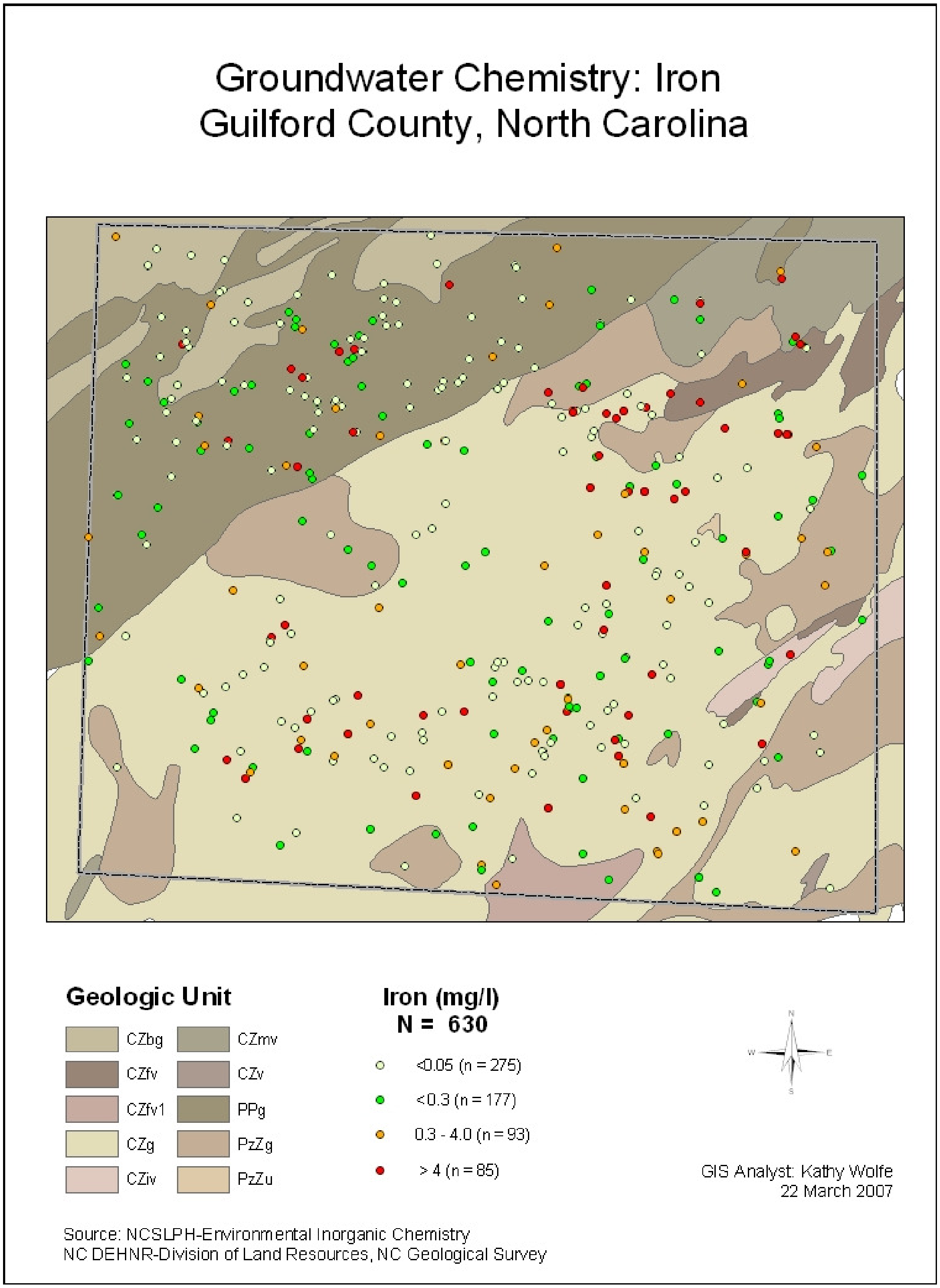

Figure 15. Iron

Geology	Well Properties	Average	Minimum	Median	Maximum	Number of Wells
CZbg	Yield (gallons per minute)	16	0	10	150	521
	Depth (feet)	263	30	240	820	521
	Water Level (feet below land surface)	31	5	30	300	521
CZfv	Yield (gallons per minute)	26	1	20	380	165
	Depth (feet)	201	45	200	520	165
	Water Level (feet below land surface)	29	3	30	50	165
CZfv1	Yield (gallons per minute)	21	1	15	100	57
	Depth (feet)	207	55	160	920	57
	Water Level (feet below land surface)	26	10	30	50	57
CZg	Yield (gallons per minute)	20	0	12	1000	2553
	Depth (feet)	231	34	200	940	2553
	Water Level (feet below land surface)	27	1	30	400	2553
Cziv	Yield (gallons per minute)	20	10	15	80	68
	Depth (feet)	222	85	200	650	68
	Water Level (feet below land surface)	29	1	30	75	68
PPg	Yield (gallons per minute)	18	0	12	200	2716
	Depth (feet)	240	29	220	930	2716
	Water Level (feet below land surface)	30	3	30	280	2716

Figure 16. Well properties by geologic unit